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Measurement of the Relative Efficiency of Highway Maintenance Patrols in Ontario

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Measurement of the Relative Efficiency of Highway Maintenance Patrols in Ontario

Author(s):	Prof. Wade D. Cook, York University; Prof. Yaakov Roll, The Technion; Dr. A. Kazakov, Ministry of Transportation, Research and Development Branch
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Ministry Contact:	Dr. Alex Kazakov (416) 235-4683
Abstract:	This report is a discussion of the result of a pilot study aimed at developing a productivity system for highway maintenance patrols in Ontario. The purpose of the project is to construct a framework whereby the efficiency of patrols can be measured relative to each other. The Data Envelopment Analysis methodology was the approach used to assess relative efficiencies of the patrols. A trial application of the DEA was undertaken in the study. Two output factors (area served and traffic intensity) and two input factors (maintenance expenditure and pavement rating) were used to assess patrol performance. The DEA approach provided relative efficiency figures which discriminate between performance levels of different patrols. Further analyses carried out included segregating patrols into groups by different discriminating characterisitics, and testing the effect on efficiency ratings of such segregation; and partioning the efficiency gaps of individual patrols to explain the inefficiency characterized by the gaps. The various portions of the gaps obtained in additional analyses hint at possible reasons for inefficiencies.
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Wade D. Cook
Professor
York University, Toronto

Yaakov Roll
Professor
The Technion, Hifa, Israel

Alex Kazakov
Ph.D.
Ministry of Transportation, Research and Development Branch, Toronto

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For additional copies, contact:
The Editor, Technical Publications
Room 320, Central Building
1201 Wilson Avenue
Downsview, Ontario
Canada M3M 1J8

Telephone: (416) 235-3480
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Executive Summary

This report discusses the result of a pilot study, aimed at developing a productivity measurement system for the highway maintenance patrols in Ontario. Productivity measurement is an effective management control tool for monitoring performance. It enables management to assess the way various units operate, to locate areas for potential improvement and, generally, to assist in making better use of limited resources to provide the required level of services.

The approach taken for assessing relative efficiencies of the patrols is known as Data Envelopment Analysis (DEA). The Data Envelopment Analysis methodology is particularly suitable for non-profit public-sector organizations. The purposes of Phase I were threefold:

(a) Test whether the DEA approach is suitable and is valid in the evaluation of road maintenance patrols.

(b) Determine whether the data necessary for applying this approach is available.

(c) Examine the kinds of analyses that can be done on the efficiency ratings obtained, and that may assist in managing the maintenance patrols. A survey of existing data was carried out, and means were developed to process this data so that it is suitable for productivity measurement by the proposed approach.

The 14 patrols in District 3 were taken as a sample for a trial application of the DEA in this study. A limited set of two output factors (area served and traffic intensity) and two input factors (maintenance expenditure and pavement rating) was chosen for assessment of patrol performance. The efficiency ratings obtained are outlined in Table 6. It can be seen that the DEA approach, making use of existing data, provides relative efficiency figures which discriminate between performance levels of the different patrols.

Moreover, a series of further analyses was carried out on the initial outcomes. These included segregating the patrols into groups by different discriminating characteristics and testing the effect of such segregations on the efficiency ratings. It was also shown that an attempt could be made to partition the efficiency gaps, which are defined as differences between present efficiency and the expected efficiency, of individual patrols to explain the inefficiency characterized by the gaps. The various portions of these gaps obtained in these additional analyses hint at the possible reasons for inefficiencies (Figures 2, 3, 4).

Futher development will centre on selecting the full set of output and input factors which are pertinent in assessing patrol performance. Also, an analytical framework will be constructed for handling a large number of patrols. The last phase will explore different avenues for analyzing the resultant efficiencies, so that the efficiency measurement system may serve as an effective management control tool.

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1/ Introduction

Routine maintenance activities in Ontario are carried out by maintenance crews from 244 patrols distributed across the province. These maintenance crews are responsible for the roadway, right - of-way and structures which fall within the patrol boundaries. Data pertaining to maintenance operations is organized within the Maintenance Management System (MMS). This computer data base provides a record of activities within the patrol in the form of accomplishments (e.g., tons of asphalt used for manual patching, man-hours used to complete the work etc.). The raw data is then summarized in various reports in the form of ratios and statistics.

The efficiency with which patrols carry out maintenance operations has become an important management issue. Observed accomplishments lead to planning values which, together with the maintenance, need inventory and influence budget decisions. A better understanding of efficiency, therefore, will give management a yardstick for measuring what accomplishments can be expected within a given budget limit. In this context important questions arise:

- Why are observed accomplishments different in one jurisdiction than in another? What should be considered as a standard?

- Are observed differences due to differences in the efficiency with which a patrol operates, or are they explainable via environment, traffic or other considerations?

- To what extent does the proportion of privatized work in a patrol influence the observed efficiency?

- How should the efficiency of a patrol be judged, given that the aforementioned factors (traffic, environment etc.) are pertinent considerations?

In managing maintenance operations across the province, the head office maintenance branch, the districts and the patrols need a gauge for deciding which patrols are or are not operating efficiently and, more importantly, what factors have the greatest influence on efficiency. This has become particularly pertinent in recent years with the substantial budget and staff reductions that have taken place. Such reductions have made resources leaner, and have, therefore, necessitated greater efficiency and effectiveness in the way these operations are managed. The recent undertakings by SHRP (Strategic Highway Research Program) in the U.S.A. and C-SHRP in Canada to define and

measure the effectiveness of different maintenance operations, further exemplify the high priority being placed in this area.

An efficiency/effectiveness measurement system such as the one proposed herein, can provide a framework to help patrols improve their standing. While a number of useful ratios and statistics are presently being generated from the raw data of the MMS which can aid in the evaluation of patrols, such indicators have significant limitations. They do not, for example, make allowance for the special circumstances (traffic, environment, degree of privatization, quality of road system) within which the patrol operates. It is the purpose, therefore, of this project, the first phase of which is discussed herein, to construct a framework whereby the efficiency of patrols can be measured relative to each other.

While well-established efficiency and productivity measurement tools exist for the "factory" environment, such tools generally rely on engineering standards (e.g., number of hours of labour needed to produce one unit of a product). In the patrol setting, however, where qualitative factors such as environment, and degree of privatization are important considerations, these conventional productivity measurement techniques are not applicable. The method to be used herein to evaluate patrol efficiency is referred to in the literature (Charnes et al.[1]) as Data Envelopment Analysis or DEA. This technique is based on defining a set of inputs and outputs which act as a form of "backdrop" against which patrols are to be evaluated. The proposed model attaches important weights to each input and output factor. The ratio of weighted outputs to weighted inputs gives the efficiency of each patrol. The method, therefore, is able to cope with the qualitative nature of the problem at hand.

Section 2 examines the model framework that will be used to analyze the relative efficiency of maintenance patrols. In particular, appropriate methods for deriving the aforementioned factor weights are discussed.

In order to evaluate efficiency and effectiveness in the proper context, the particular circumstances within which maintenance patrols operate must be considered. This is the scope of Section 3. It is these circumstances which have a crucial bearing on which output factors best represent what the patrol maintenance accomplishes, and which input factors influence the capabilities of the patrols to achieve their mandates.

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[1] A. Charnes, W.W. Cooper & E. Rhodes, "Measuring the Efficiency of Decision Making Units," European Journal of Operations Research, vol. 2, no. 6, 1978, pp. 429-444.

Section 4 details the results of a pilot application of this efficiency measurement tool to the 14 patrols in District 3. In Phase I, or pilot phase of the project, the analysis leads to a rank ordering of the patrols in relation to one another (based on the limited set of chosen factors). In addition, Phase I touches upon other areas of analysis which will be explored in more depth in later phases. These areas include:

(1) Separation of patrols into special subgroups for separate analysis according to factors, such as degree of privatization used or percentage of commercial vehicles serviced.

(2) Examination of the total efficiency gap for a patrol, and the extent to which this efficiency gap can be explained by the special circumstances (e.g., severe environment) within which the patrol operates.

Section 5 is devoted to concluding remarks and a description of proposed directions for later phases of the project.

2/ A Model for Measuring the Relative Efficiency of Maintenance Patrols

2.1/ Conventional Approaches to Productivity and Efficiency Measurement

The productivity or *efficiency* level of any Decision Making Unit (DMU), (e.g., factory, government department, maintenance patrol) is a measure of the extent to which that DMU makes the best possible use of a given set of *inputs* (resources, etc.) to produce some set of *outputs*. Conventionally, efficiency is represented by the ratio of the minimum amount of inputs that could be used (to produce its outputs) to the actual inputs consumed. In this context, "best possible use" loosely means getting the most out of available resources within a given set of circumstances.

In an industrial setting, efficiency or productivity is usually approached from an engineering perspective. This approach is based upon production standards. Such standards specify the best (minimal) amount of each input needed to produce one unit of output. The productivity of a DMU is therefore given by the ratio of standard or required inputs (needed to create the current level of output) to the actual inputs used.

Other measures of efficiency/productivity often found in organizations are based on *financial* information. Profitability measures, such as return on investment, provide a type of performance indicator. Such measures are common in profit-making settings. In a non-profit (typically public sector) environment, one might, for example, compare what the cost could be if jobs were done privately to the actual costs under the current setting.

2.2/ The Data Envelopment Analysis Method for Relative Efficiency Measurement

An alternative to these *absolute* approaches to efficiency measurements is the Data Envelopment Analysis (DEA) method for measuring the *relative* efficiency of a set of DMUs. This technique was designed specifically for examining the efficiency of organizations in which qualitative factors must be taken into consideration. Thus, that type of model is well suited to the maintenance area, since factors such as traffic intensity, environmental conditions, average age of pavements and safety parameters are an important part of the picture. Moreover, unlike in the production setting, factors are not generally reducible to a common unit (e.g., dollars or hours). The DEA model also is particularly pertinent in that it allows for the measurement of factors on different scales—number of accidents, maintenance dollars, cars/day, average age of pavements, etc.

In order to demonstrate the DEA method for measuring relative efficiency, consider the following simple example of seven patrols in which a single output Y (e.g., number of lane kilometres serviced by the patrol) is observed, and two inputs are used. Take the two inputs to be X_1 = number of hundreds of thousands of dollars from the maintenance budget, and X_2 = the average road conditions as assessed by Pavement Condition Rating (PCR). Let's further simplify matters by assuming that all patrols service the same number of lane kilometres, so Y does not differ from patrol to patrol. Let the respective inputs for this group of patrols be as follows:

patrol	A	B	C	D	E	F	G
X_1 ($000000)	3	5	8	12	6	8	10
X_2 (PCR)	.90	.70	.55	.50	.84	.80	.60

A picture of these seven sets of inputs is shown in Figure 1. It can be seen that different patrols use different combinations of X_1 and X_2 , however some patrols use less inputs than others (for rendering the same output Y). By joining the points representing patrols A, B, C and D, it becomes clear that these 4 patrols "dominate" the entire group in the sense that no other patrols use better combinations of inputs. Thus, patrols A, B, C and D can be thought of as forming an *efficient frontier*.

Any patrol on the frontier is regarded as "efficient" in a relative sense and is defined as having an efficiency rating of 1.0. The patrols behind the frontier are inefficient relative to those forming the frontier. Thus the frontier *envelops* the points representing all patrols (hence the name Data Envelopment Analysis).

The efficiencies of patrols E, F and G can be measured relative to the efficient frontier. Consider, for example, patrol E which is dominated by patrol B. It has inputs in the same proportions as B, but larger by 20%. The relative efficiency of patrol E is 100 over 120 = 0.83 or 83%. Graphically this is represented by the ratio of distances 0B to 0E in Figure 1. Patrol F is similarly dominated, although by a combination of B and C. The efficiency of F is obtained from the ratio 0K/0F in Figure 1. Patrols B and C constitute the *peer group* or comparison group against which the efficiency of patrol F is measured. Patrol B is the peer group for patrol E.

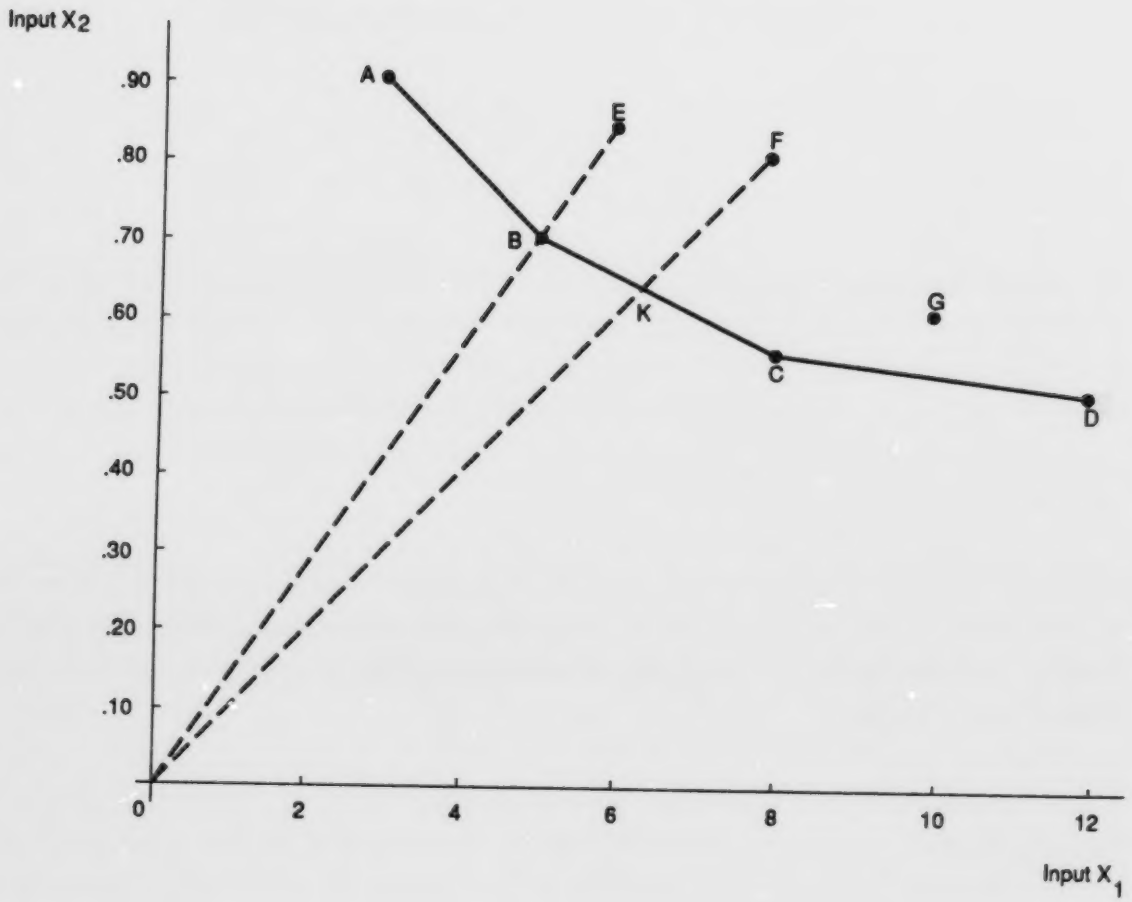


Figure 1/ Efficient Frontier

In the simple example with only a single output and two inputs, one can measure efficiency directly from a graphical representation, like the one in Figure 1. This kind of representation does not highlight the weights given to factors in determining efficiencies; the weights are embedded in the scales of the two axes of the graph. In the more complex case of multiple inputs and outputs, the measures of efficiency cannot be arrived at in as simple a manner. In the general case it is necessary to solve an optimization problem, using linear programming techniques, in order to obtain efficiency ratings for the various units, their peer groups and the weights accorded to the different input and output factors.

Appendix A1 gives a mathematical description of the general DEA model. In words, the model determines the best set of input weights V_{io} and output weights U_{ro} such that the ratio of total weighted outputs to total weighted inputs e_o, is maximized for each DMU_o. This is done subject to the constraints that the corresponding ratio (calculated with the optimizing set of weights) for each DMU, including the one in question, does not exceed 1.0. This means that the highest efficiency score for any DMU is 100% and that the weights U_{ro} and V_{io} fall within some set of reasonable bounds. The ratio e_o is the relative efficiency rating for DMU_o.

In the production setting, the factor weights are generally the prices associated with inputs and outputs. If, for example, different classes of labour represent the inputs, and if it is desirable to construct a single labour productivity ratio, the weights on the different inputs would simply be the differential labour rates. Thus, dollars become the common basis of comparison of inputs.

The rationale for determining the best set of factor weights for DMU in the case of maintenance patrols is that, since non-economic factors are present, there is no "correct set" of weights that applies to all patrols. The importance, for example, of environmental factors to some patrols (e.g., in Kenora) may be different than to other patrols (e.g., in London). Thus, rather than having to try to assign some set of common weights to inputs and outputs, the model itself chooses weights that are appropriate for each patrol. In choosing weights for any patrol, the DEA model tries to present the patrol's position in the *most favourable light* ; the weights are selected to maximize its efficiency. In this setting, if a patrol can be shown to be efficient (has a ratio of 1.0) by some reasonable set of weights, then such will turn out to be the case. A patrol will only be declared *inefficient* if, even in such a favourable situation, it has failed to be 100% efficient. In other words, it is *dominated* by other patrols or combinations of other patrols. DEA should, thus, be viewed as a technique for identifying inefficiency.

An added feature of the Data Envelopment Analysis structure is its capability to study the impact of various factors in several ways. Suppose that an important management issue is the extent to which privatization influences maintenance effectiveness. Privatization policy could be analyzed in two ways within the DEA framework. One approach would be to divide the single maintenance budget variable into two separate variables (e.g., privatized money and in-house money). This has the *indirect* effect of desegregating patrols in that a further dimension has been added to the problem. An alternate approach is to *directly* desegregate patrols by separating them into two groups (e.g., those with less then 20% privatized work and those with more than 20% privatized work). In this manner, one can study the importance of a particular element such as privatization policy.

For purposes of measuring the relative efficiency of a set of maintenance patrols the DEA approach has many benefits. These include:

(1) Rank Orders Patrols

The model provides a rank ordering of the patrols in terms of their efficiency rating. As a management tool, this gives an overall measure of the relative standing of the patrols, as well as an indication of the possible reasons behind any given patrol's inefficiency.

(2) Peer Group Comparisons

In the process of calculating an efficiency rating for a given patrol I, a small subset of efficient patrols is identified. It is this peer group against which others are evaluated, and to which others should strive to emulate.

(3) Clearly Efficient, Clearly Inefficient and Middle-of-the-Road Patrols

By repeating the analysis, and applying several versions of the model, three major groups emerge. The first group consists of those patrols which rate *high*, regardless of which version of the model is used. The second group is that set which consistently rates *low* under different model versions. Finally, there is the *unstable* third set whose ratings fluctuate widely, depending on the input and output weights determined by the model.

(4) Multiple Inputs and Outputs

As indicated earlier, the DEA method accommodates multiple inputs and outputs. Of particular importance is the fact that non-economic factors can be included in the analysis. Weights on these factors are calculated within the model in a manner which takes into account the particular circumstances of each patrol, and hence, presents each patrol in the most favourable light. The outcome of a DEA will highlight specific areas where more in-depth engineering studies should be carried out.

(5) Analysis of the Impact of Circumstances in Which Patrols Operate

The DEA can be carried out in many different settings. Patrols in the north, for example, can be analyzed in isolation. Patrols for high-volume pavements can be separated for individual analysis. Thus, the special circumstances of subgroups of patrols can be pin-pointed, and a specific DEA targeted at those circumstances.

(6) Controlled Weights

The DEA model is very flexible in the sense that the user can impose restrictions on the weights to be assigned to inputs and outputs. For example, if safety is considered to be the predominant output factor, the model can be controlled so that the weight on this factor is higher than those assigned to other outputs.

(7) Uses Existing Data

An important feature of the DEA approach is that it is based upon existing maintenance and highway inventory data. No costly data collection procedures are required other than those already in place.

3/ DEA In the Maintenance Environment

3.1/ Patrol Maintenance

Activities have been organized within the MMS under more than 200 different operations categories covering both preventive and corrective work. In broad terms, maintenance operations can be classified under the headings:

- surface
- shoulder
- right-of-way
- median
- winter operations

Surface and shoulder operations include, for example, all forms of manual and machine patching and sealing. Right-of-way and median operations involve grass mowing and vegetation control, signs, lighting, guard rails, etc. Winter operations generally pertain to snow removal, salting and other winter safety measures. To a great extent the work of patrol crews is safety related.

Each of the 244 patrols across the province is responsible for some fixed number of lane kilometres of highway. When the maintenance work load exceeds patrol capacity, the excess is carried out by private contractors.

3.2/ Selection of Factors

In the application of the Data Envelopment Analysis methodology, two critical steps are involved at the outset. First it is necessary to select a set of Decision Making Units. These should be relatively autonomous bodies which all perform a similar function. In the case at hand, a maintenance patrol is considered to be a DMU, although technically one could use the group of patrols in a district as the DMU. This is a matter of preference and, for purposes herein, the use of the single patrol is legitimate.

The second step is that of selecting a set of input and output factors. Outputs should, to a large degree, measure the effectiveness of what patrols do to carry out their mandate. Thus, while the measurement of efficiency pertaining to individual maintenance processes is important in itself, our goal is to capture the overall effectiveness of the road maintenance effort. From this point of view, potential outputs or *effects* of road maintenance would include:

- level of quality at which roads are maintained
- rate of (road condition related) accidents
- volume of traffic served

Inputs or *causes* of maintenance effectiveness can be of different types. There are controllable factors such as the size of the maintenance budget, and the percentage of work done under private contract. Other factors, not under the control of the patrol or the district, are such things as environmental conditions (e.g., inches of snowfall), and average age of pavements that the patrol must deal with. To an extent, these latter factors describe the *circumstances* within which a patrol is forced to operate, and may, therefore, have a very strong influence on the way in which outputs can be affected.

The process of selecting factors to use in a DEA model should concentrate on finding the *effects* of maintenance activities together with a set of explanatory or causal factors that create those effects.

3.3/ Data and Quantification Issues

The choice of factors (outputs and inputs) must, of course, be guided by another very important consideration, namely *data availability*. There are limitations on the extent to which effects of maintenance can be observed. There are not, for example, observed pavement condition ratings on each section of highway *immediately before and after* surface maintenance operations, nor is there reliable information as to the extension in pavement life attributable to the maintenance activities. Thus, it is difficult to separate out that portion of year-to-year pavement condition rating changes that are due to maintenance efforts. Similarly, while there is reliable data as to daily traffic on a pavement (AADT), the user cost in terms of tire wear etc. is difficult to obtain. Therefore, to a great extent, existing data sources tend to dictate what can and cannot serve as inputs and outputs.

Having chosen those factors to be used to describe cause and effect (factors for which data exists), the issue of appropriate *quantification* arises. While it is true that the DEA structure does not require that factors be reducible to a common unit, it is necessary to quantify each on some scale.

If safety is a principal consideration in regard to maintenance effort, some reasonable method of capturing safety (e.g., skid resistance, number of accidents, number of fatal accidents, etc.) must be found. Severity of the environment is an important determinant of the extent to which patrol efforts can be effective. Yet, there is no obvious single measure of environmental impact. Again, quantification is a pressing issue in the selection of factors.

The grouping of various indicators into a set of overall or *composite factors* also influences the final structure of the DEA model. As described earlier, the model is based upon a set of inputs and outputs which describe cause and effect. However, as pointed out above, there can be several different measures that describe the same factor (e.g., accidents). While technically the model could handle many different indicators of the same factor (thus avoiding the grouping problem), it is highly desirable to arrive at a small number of inputs and outputs. If, for example, we desire as an output "size of system serviced", it becomes necessary to describe on a single scale such measures as the number of lane kilometres of paved surface, the amount of paved versus gravel shoulders, the number of hectares of right-of-way, etc. Environmental indicators such as inches of snowfall, number of freeze/thaw cycles, etc., should be combined into some composite factor.

Finally, with regard to data availability and quality, there are time-frame issues. Data from different sources may not cover the same time-frame. Consequently, all data has to be brought to a common time-frame. The "natural" unit of time, for measuring efficiency in our case, is a fiscal year. However, because of the relatively long period of time which may elapse between the making of decisions in the field and obtaining the corresponding efficiency figures, another technique—known as "window analysis"—will be examined. Using this technique, although all calculations would still cover an entire year, efficiency figures could be obtained quarterly for the year ending with that quarter.

3.4/ Development Phases

Despite the various issues and reservations raised in the previous subsection, the DEA approach appears to be the most viable in regard to evaluating the efficiency of maintenance patrols. The development of the model for measuring patrol efficiency is designed to proceed in three phases: (I) The Model; (II) The Factors; and (III) Analysis. The scope of these phases is outlined in Table 1.

Facet \ Phase	I	II	III
The model	Testing whether the DEA model is applicable to maintenance patrol efficiency measurement	Preparing framework for handling a large number of patrols	Setting up a computer program for continous monitoring of patrols efficienies, and analysis of outcomes
The factors	Selecting initial factors: 2 outputs 2 inputs	Defining all output and input factors to be entered into the model	Further "fine tuning" of some factors
Analysis	First try at subgrouping the patrols	Testing possibilities of analysis by district, region etc., as well as by various other characteristics of patrols	Analysis of efficiency gaps
Number of patrols involved	14 (one district)	50-60 (3-4 districts)	All patrols

Table 1: Phases of the project

Phase I, to be discussed in the next section, has concentrated primarily on the modeling aspects of the development. This phase acted as a pilot or demonstration run of the DEA methodology. Phase II will centre mainly on developing the full set of factors (inputs and outputs) which will be used to evaluate the relative efficiencies of patrols. A larger set of patrols will be used than was the case in Phase I. Much of Phase II will also examine various categories of analysis (e.g., by region, district, traffic class, etc.). Finally, Phase III will carry out a full implementation of DEA across all patrols. Computer programs will be created for developing all composite input parameters, and for carrying out the requisite optimization runs.

4/ A Pilot Study of DEA in Maintenance

4.1/ Framework of the Study

The applicability of the DEA model in the area of pavement maintenance was assessed in the pilot study, reported here. Specifically, this study has accomplished the following goals:

(1) An examination of existing data sources was undertaken to determine if there is adequate information available to support an analysis of relative efficiency.

(2) A trial set of cause and effect indicators (inputs and outputs) was selected to get an initial view of how patrols compare in an efficiency sense, and what factors appear to influence that efficiency.

(3) The DEA model was tested to determine its capability to discriminate among patrols vis-a-vis their efficiency. That is, the extent to which the model can delineate between winners and losers was investigated.

(4) A test of the impact of putting bounds on the factor weights was carried out to determine the sensitivity of the ranking of the patrols to such modifications.

For this purpose, a set of 14 patrols spanning one district (District 3) was selected as the DMUs for analysis. Appendix A2 provides a map of these 14 patrols.

Two inputs and two outputs were chosen for analysis purposes in the pilot stage. On the output side, the first factor is a composite measure of various "size of the system" indicators. This Assignment Size Factor (ASF) combines values relating to the various components—surface, shoulder, right-of-way, median, and winter operations. The differences in surface and shoulder types have been accounted for, using the levels of expenditure on the respective types in the most recent fiscal period (see Appendix A3). The other output factor is the Average Traffic Serviced (ATS) indicator. This indicator combines AADT and road length, and therefore expresses total vehicle kilometres.

On the input side, one economic factor and one non-economic factor were used. These were: Total Patrol Expenditure (TEX) and Average Pavement Condition Rating (APR).

The process for calculating values of the four factors is described in Appendix A3. As an example of the calculations involved, Appendix A4 gives the computer output corresponding to patrol 14 in District 3. The input to the computer program used to compute the factor values is the information pertaining to the set of road sections that makes up the patrol in question. For each section serviced by the patrol, the length, surface type and number of two-lane equivalents, shoulder type and width, PCR, AADT and PT (the percentage of trucks) were obtained from the Maintenance Management System and Highway Inventory data bases. Appropriate software for accessing and extracting the relevant data from these sources was designed by the Ministry of Transportation, Research and Development Branch.

Table 2 provides the complete list of factor values for the 14 patrols.

In compiling the information needed to compute the required factor values, various data sources were investigated, including the provincial highway inventory data base, MMS file, PMS file and the maintenance branch inventory files. The primary source of information for the analysis carried out to date has been the highway inventory data augmented by the distribution of inventory sections by patrol. To this point, the analysis has not involved accident and safety related information nor environmental considerations. The investigation to be carried out in Phases II and III will necessitate accessing these and other data sources.

4.2/ Outcomes of the Analysis

As described earlier, the DEA model involves solving a linear programming problem for each patrol in order to determine its efficiency standing in relation to the other patrols under consideration (see Appendix A1). In the particular case at hand, 14 such problems were solved. Appendix A5 provides a sample solution of one such problem for patrol 14 of District 3. In this case, the bounded model is being run. A discussion of bounded and unbounded models follows. The efficiency rating for this specific patrol is given by the objective function value = 0.613. Some explanation of the remainder of the output is included in the Appendix.

Various versions of the DEA model were developed for this study and are used for analysis of maintenance efficiency. In particular, a model was developed which allows one to impose certain "bounds" on the factor weights. Both the unbounded and bounded models, and the associated results are discussed on the following pages.

Patrol	(ASF) Assign. size	(ATF) Traffic served (10,000 veh. km)	(TEX) Total expenditure ($000)	(APR). Ave. pavement rating (%)
1	696	39	751	67
2	616	26	611	70
3	456	17	538	70
4	616	31	584	75
5	560	16	665	70
6	446	16	445	75
7	517	26	554	76
8	492	18	457	72
9	558	23	582	74
10	407	18	556	64
11	402	33	590	78
12	350	88	1074	75
13	581	64	1072	74
14	413	24	696	80

Table 2: Summary of factor values

4.2.1/ Unbounded Model

In the first round of analyses of the patrols, the linear programming model of the type described in Appendix A1 was run without upper and lower bounds on output and input weights M_1, M_2, and N_1, N_2 respectively. Table 3 shows the results of this set of runs.

The table displays—for each patrol or DMU—the efficiency rating e, and weights M_1, M_2, N_1 and N_2. It is noted that those patrols showing an efficiency rating of 1.0 are classified as efficient and lie on the efficient frontier. (An efficiency rating of 0.803 for patrol 3, for example, is interpreted as meaning that, technically this DMU is only about 80% as efficient as it could be.)

The column labelled "DMUs in facet" gives the peer groups. Recalling the earlier example of Figure 1, patrols B and C constitute the peer group for patrol F. In the case of Decision Making Unit 3, patrol 3, the relevant peer group consists of patrols 4 and 8. Specifically, in evaluating its

efficiency standing, patrol 3 should compare itself to efficient patrols 4 and 8, each of which has a rating of 1.0 or 100%. It is to these two patrols which DMU 3 should strive to emulate.

More generally, the efficient frontier consists of facets created by the efficient patrols 1, 4, 8, 12 and 13. It is the combinations or facets of these patrols against which all others are evaluated. The efficient pair of patrols 1 and 4 forms the peer group for inefficient patrols 2, 5, 9 and 10. Efficient patrol 12 must be added to this group (to give 1, 4, 12) to obtain the peer group for patrols 11 and 14.

4.2.2/ Bounded Model

In the unbounded case described above, the sets of weights obtained for the 14 patrols vary widely. It is noted, for example, that $M_2 = 0.00001$ for DMU 1 but $M_2 = 0.017883$ for DMU 11. Technically speaking, patrol 11 is permitted to attach a much greater weight or importance to the second input, traffic, than that given by patrol 3. Flexibility in the sets of weights is a desirable feature; it allows for the different circumstances of the patrols. As discussed earlier, such flexibility should be reasonably limited. In that regard, some bounds were imposed on the range over which the M_r and N_i weights would be allowed to move. The procedure for establishing bounds essentially involves using representative values from the ranges for weights that arise from the 14 unbounded runs. While at present the procedure for setting these limits is quite arbitrary, it is the intention in future phases of the project, to formalize this procedure.

Table 4 presents the outcomes from the bounded version of the 14 linear programming runs. Generally, the efficiency ratings did not change drastically, although in a pure definitional sense only three of the patrols (1, 4 and 8) are now efficient. Patrols 12 and 13 which previously, with complete freedom to choose weights, formed part of the efficient frontier, are now behind the frontier with efficiency ratings at 0.91 and 0.87, respectively. Of course, under this new scenario, there are fewer *different* peer groups. The set of patrols 1 and 4 constitutes the peer group for the five inefficient patrols 2, 5, 9, 10 and 14.

It is noted that all efficiency ratings are at or are lower than their previous (unbounded) levels. This is due to the restricted freedom of movement of the weights in the bounded case.

Table 3
Outcomes with the Unbounded Model

DMU	EFFICIENCY	WEIGHTS ($X10^6$)				*DMU*, IN FACET	SLACKS			
		*M*1	*M*2	*N*1	*N*2	(PEER GROUP)	*S*1	*S*2	*R*1	*R*2
1	1	1436	10	913	4690	1	—	—	—	
2	.999	1621	10	1030	5292	1,4	—	6.141	—	—
3	.803	1760	10	1688	1312	4,8	—	5.578	—	—
4	1	1623	10	1557	1210	4	—	—	—	—
5	.860	1535	10	976	5013	1,4	—	13.969	—	—
6	.931	2087	10	2246	10	8	—	.317	—	4.553
7	.885	1585	2501	1804	10	4,8	—	—	—	4.258
8	1	2032	10	2187	10	8	—	—	—	—
9	.913	1635	10	1039	5339	1,4	—	5.173	—	—
10	.724	1778	10	1130	5806	1,4	—	3.205	—	—
11	.874	708	17883	1697	10	1,4,12	—	—	—	13.365
12	1	389	9815	930	10	12	—	—	—	
13	1	808	8291	90	12208	13	—	—	—	—
14	.619	742	13041	1114	2805	1,4,12	—	—	—	—

Table 4
Outcomes with the Bounded Model

DMU	EFFICIENCY	WEIGHTS ($X10^6$)				*DMU*, IN FACET	SLACKS			
		*M*1	*M*2	*N*1	*N*2	(PEER GROUP)	*S*1	*S*2	*R*1	*R*2
1	1	1833	500	1183	6000	1	—	—	—	—
2	.995	1833	500	1189	6000	1,4	—	6.070	—	(.506)
3	.800	2180	500	2070	1336	4,8	(1.313)	5.513	—	—
4	1	2100	500	2070	1337	4	—	—	—	—
5	.854	1833	500	1189	6000	1,4	—	13.802	—	(1.150)
6	.929	2100	500	2233	300	8	(.719)	291	—	4.576
7	.884	2100	6093	2500	300	4	(.355)	—	(.213)	4.261
8	1	.2180	2704	2320	300	8	—	—	—	—
9	.910	1833	500	1190	6000	1,4	—	5.115	—	426
10	.722	1834	500	1190	6000	1,4	—	3.168	—	(.264)
11	.803	800	10000	1336	300	4	97.570	(7.859)	—	1.790
12	.913	800	10000	900	4043	1	361.709	(48.120)	213.145	
13	.876	800	10000	900	4044	1	90.895	(26.351)	211.989	
14	.614	800	10000	1001	2936	1,4	18.713	(1.497)	—	—
Upper Bounds:		2100	10000	2500	6000					
Lower Bounds:		800	500	900	300					

4.3/ Directions for Further Analysis

4.3.1/ Common Set of Weights

An important feature of the DEA approach, but in some respects a bothersome one, is its derivation of a different set of weights M_r, N_i, for each patrol. On the positive side, one can view this as a mechanism for highlighting the strengths of each patrol and at the same time taking into account the special circumstances in which the patrol operates. On the negative side, there is the belief (at least from an engineering and economist perspective) that there should be a single set of weights that applies to all DMUs. Such is certainly the case when the inputs and outputs can all be expressed in economic terms—in a factory with inputs such as labour, capital and materials. Recall the earlier reference to standards .

While the concept of a completely *common set of weights* (CSW) in the non-profit sector may not be fully justified, it is worth examining the phenomenon. In this regard, a procedure was developed for deriving such a set. The approach essentially amounts to closing the gap between the upper and lower limits on the weights used in the bounded analysis discussed in the previous subsection. The efficiency ratings from this analysis are given in a summary table, Table 6.

4.3.2/ Desegregation of Factors; Patrol Grouping

The factors (inputs and outputs) chosen for this pilot study will be re-evaluated in the later phases of development. One important area to be studied in these later phases will be that of factor desegregation. Consider the output factor ATS, which is equal to the product AADT x length. One can investigate modifications of this composite factor to allow for an evaluation of the impact of commercial vehicles in the AADT, which can be used as an output factor.

As already pointed out, desegregation can be accomplished in one of two ways. First the factor itself (Average Traffic Serviced) can be augmented or replaced by two or more separate factors (e.g., ATS plus percentage of commercial vehicles). The DEA model would compute a weight for each of these factors. Of course, each such new factor added tends to make the model too sensitive to specific patrol factors, and in the limit (i.e., adding too many such factors) all patrols could appear efficient. As an alternative, the issue of percentage of trucks can be dealt with by splitting the set of all patrols into two or more groups according to this percentage. One could, for example, do an analysis of those patrols where the percentage of commercial vehicles (average on all pavements in the patrol) is above 15%, and a separate analysis for those patrols where the

percentage of commercial vehicles is below 15%. In this manner, a more homogeneous group is being examined, and the model can concentrate on discriminating among patrols on the basis of the remaining factors.

As an example of the second form of desegregation, the factor representing percentage of work carried out by private contractors was investigated. Group A consists of those patrols in which the percentage of work privatized was 20% or more. Group B consists of patrols which privatized less than 20% of work, as measured in total dollars spent. Table 5 presents the results of this analysis. The relative efficiency of any patrol will be at least as high under the desegregated analysis as under the analysis when all patrols are included. This is logical. When group A, for example, is subjected to a separate evaluation, any given patrol such as patrol 3 is being compared to fewer other patrols (8 others) than in the original analysis (13 others).

In this particular evaluation, efficiencies seemed to have changed very little. Clearly, in cases where the peer group for a patrol remains the same, no change in the efficiency rating will occur. For example, in both analyses, patrol 7 has patrol 4 as its peer group. Thus, patrol 7 receives the same rating under both evaluations. Patrol 3 on the other hand, has DMU 4 and 8 as the peer group originally, and a rating of $e = 0.80$. Under the desegregation, patrol 3 (in group A) has DMU 2 and 6 as the peer group, and a rating of $e = 0.82$.

Outcomes of the various versions of the Data Envelopment Analysis for obtaining relative efficiencies are summed up in Table 6. These outcomes can be used to segregate the analyzed set of patrols into several efficiency classes. The first class contains patrols with consistently high efficiency ratings, in any kind of analysis attempted. Patrols 1, 2, 4 and 8 of the sample belong to this class. The second class, patrols 5, 6, 7, 8 and 11, is made up of those patrols with intermediate relative-efficiency ratings, while patrols 3, 10 and 14 belong to a third class having consistently low scores. A final class, patrols 12 and 13, comprises the units for which outcomes vary significantly with different kinds of analysis. Such patrols should be examined closely for specific factors affecting their performance.

Table 5
Outcomes when DMUs are grouped by % privatization

GROUP	DMU	EFFICIENCY	WEIGHTS ($X10^6$)				*DMUs* IN FACET	SLACKS			
			*M*1	*M*2	*N*1	*N*2	(PEER GROUP)	*S*1	*S*2	*R*1	*R*2
A	1	1	2100	2011	1515	6000	1	—	—	—	—
	2	1	2100	2012	1516	6000	2	—	—	—	—
	3	.820	2100	500	1760	3305	2,6	(.302)	1.268	—	—
	5	.85	1926	500	1276	6000	1,2	—	9.898	—	(.825)
	6	.929	2100	500	2233	300	8	(.719)	291	—	4.546
	8	1	c2100	500	2237	300	8	—	—	—	—
	10	.732	1829	10000	2020	2124	1,2,8	—	—	—	
	13	.874	800	10000	900	4044	1	90.895	(26.351)	(211.989	
	14	.646	800	10000	1234	300	1	3.754	(.647)	—	11.570
B	4	1	2100	500	1471	6000	4	—	—	—	—
	7	.88	2100	6093	2500	300	4	(.355)	—	(.213)	(4.261)
	9	.91	1558	500	900	6000	4	—	5.081	909	(.560)
	11	.803	800	10000	1336	300	4	97.570	(7.859)	—	1.790
	12	.933	800	10000	900	3697	4	224.497	(59.089)	456.987	
	Upper Bounds:		2100	10000	2500	6000					
	Lower Bounds:		800	800	900	300					

There is no general rule regarding which of these two forms of desegregation, all patrols in one group or two groups with different levels of privatization, is the most appropriate. The first method carries the danger of too much inter-correlation among factors being created. As previously pointed out, with too many factors all patrols can appear efficient. Rather than the model becoming more discriminating, the reverse is true. The second method has disadvantages as well. Group sizes, when the set of patrols is split up, can become too small for the results to be meaningful.

These types of analyses will be investigated in detail in the second and third phases of the project.

Patrol	Unbounded Runs	Common Weights	Bounded Runs Individual Weights		
			All Patrols	Group A	Group B
1	1	.947	1	1	
2	.999	.955	.996	1	
3	.803	.774	.800	.820	
4	1	1	1		1
5	.860	.780	.854	.857	
6	.931	.862	.929	.929	
7	.885	.873	.884		.884
8	1	.943	1	1	
9	.913	.889	.910		.911
10	.724	.697	.722	.732	
11	.874	.696	.803		.803
12	1	.518	.913		.933
13	1	.653	.874	.874	
14	.619	.586	.614	.646	

Table 6: Efficiency ratings

4.3.3/ Efficiency Gap Analysis

The observed inefficiency ($\bar{e} = 1.0 - e$, where e is the efficiency rating) of any patrol can be explained or rationalized as consisting of different types of efficiency *gaps*. Figure 2 defines different types of gaps and presents a possible analysis of such gaps. Briefly, (see Figure 2) if one takes the efficiency e arising from the Common Set of Weights (CSW), for patrol 14 the Common Set of Weights rating is $e = 0.586$, the resulting *total efficiency gap* is given by 1.0 - 0.586 = 0.414. This total inefficiency of 0.414 under the CSW can be viewed as a sum of the inefficiencies. A 2.8% portion of this gap can be closed if freedom of choice of weights is permitted for patrol 14 (at least in the bounded sense). One can perhaps rationalize this improvement by reasoning that special circumstances surrounding patrol 14's "environment" are not given proper consideration when the CSW rating is used.

An even further improvement in the rating to $e = 0.646$ is achieved when patrol 14 is evaluated as part of the patrols of group A that all have a similar privatization policy. This portion (.646 - .614 = .032) of the total efficiency gap is therefore explainable by the type of privatization policy used. The remaining 0.354 or 35.4% of the gap is unexplained insofar as the present level of analysis is concerned.

Similar scenarios are shown for patrols 3 and 12 (see Figures 3 and 4). It is noted that the unexplained portion of the inefficiency can differ widely from one patrol to another. It is this unexplained portion of the efficiency gap with which the patrol supervisor must be most concerned.

The issue of gap analysis will be pursued further in later phases of the study.

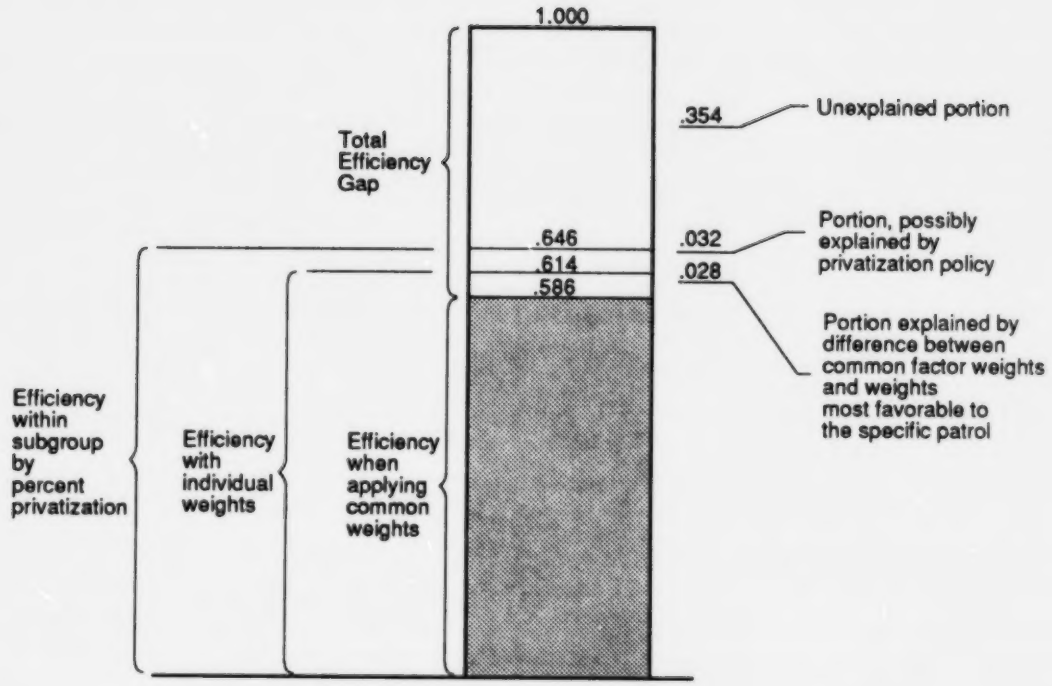


Figure 2/ Efficiency picture for patrol 14

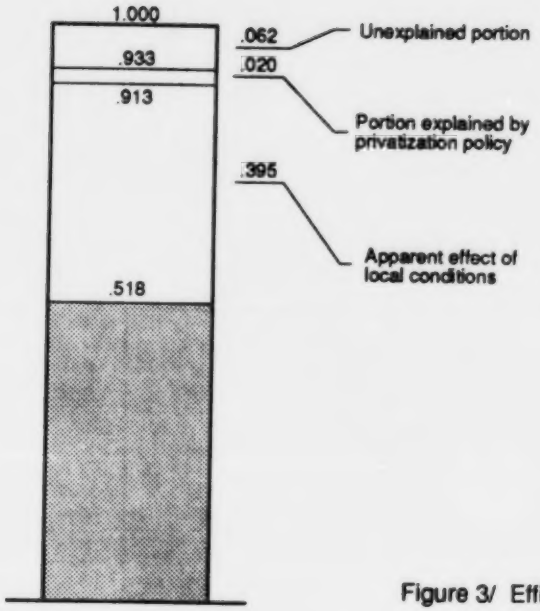


Figure 3/ Efficiency picture for patrol 12

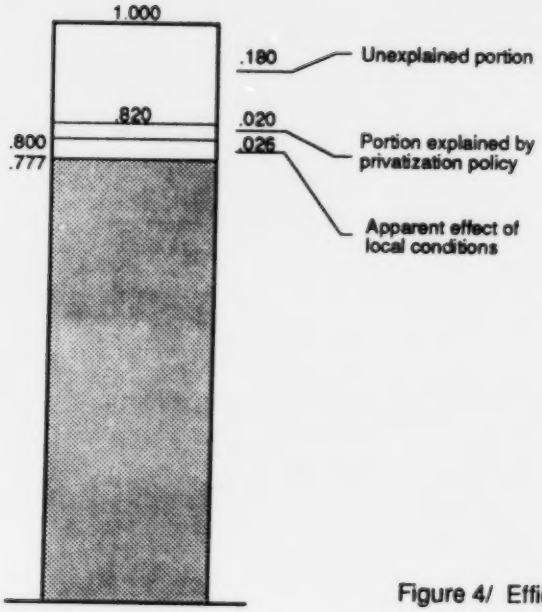


Figure 4/ Efficiency picture for patrol 3

5/ Conclusions

This pilot study of maintenance patrol efficiency has concentrated primarily on model testing via an analysis of 14 patrols in a single district. Various levels of evaluation were carried out ranging from the unbounded calibration of patrol ratings to the bounded and common weights values.

In addition, two other areas of analysis were carried out in this test mode. The desegregation analysis is aimed at isolating subgroups of patrols which have some commonality on the basis of particular factors (e.g., percentage of privatization, percentage of trucks, geographical factors such as northern versus southern patrols). An alternative form of desegregation can be facilitated through the inclusion of additional factors in the model (e.g., an environmental factor or dummy variable which distinguishes northern from southern patrols). The second type of analysis is an evaluation of efficiency gaps in an attempt to *explain* the causes of inefficiencies.

The results of this pilot study demonstrate that the DEA technique is suitable for the measurement of the relative efficiency of maintenance patrols. The MMS data bases augmented by the data from Pavement Management System or Pavement Inventory Data, Accident Data, and Data from Environment Canada is sufficient for the analysis. The general system of preparation of the data from some of the mentioned data bases is developed; others are in the process of development.

More work should be done on the selection of relevant input and output variables and the development of models for efficiency gap analysis.

Appendix A1

The DEA Model

In this section the mathematical formulation of the Data Envelopment Analysis is presented. Then an equivalent Linear Programming Model is described and a sample of the solution of the equivalent LP Model is presented.

The efficiency of the decision unit "i" is calculated as:

$$e_i = \frac{\Sigma_r U_{rj} Y_{ri}}{\Sigma_k V_{kj} X_{ki}} \qquad (1)$$

where

U_{rj}, V_{rj} are weights for output and input factors correspondingly; index j indicates that the weights selected for the analysis of patrol "j" are used for estimation of the efficiency of patrol "i".

Y_{ri} is an input factor "r" for patrol "i", for example, total expenditure of patrol "i" is one of the input factors in this pilot study.

X_{ki} is an output factor "k" for patrol "i", for example, Average Traffic Serviced expressed in total vehicle-kilometres.

The model singles out a patrol "o" and allows the weights U_{ro} and V_{ko} to vary to maximize the efficiency as calculated by (1) with i=o and j=o, so the maximum of the following expression is searched:

$$\max \qquad e_o = \frac{\Sigma_r U_{ro} Y_{ro}}{\Sigma_k V_{ko} X_{ko}} \qquad (2)$$

The problem has no solution until some additional restrictions are applied. It is clear, that if the weights U_{ro}, V_{ko} can take any value from zero to infinity, no maximum can be found.

The logical restrictions on the weights, applied in the DEA model, limits the efficiency of any Decision Making Unit including that of "o" when calculated with the set of weights maximizing the efficiency of unit "o" to 1.0 or 100%. In mathematical notations the constraints are:

$$e_j = \frac{\Sigma_r U_{ro}\, Y_{rj}}{\Sigma_k V_{ko}\, X_{kj}} \quad \leq \quad 1.0 \quad \text{for all j;} \qquad (3)$$

$$U_{ro} \quad > \quad 0 \text{ for all output factors r}$$

$$V_{ko} \quad > \quad 0 \text{ for all input factors k}$$

The above can be transformed into a standard linear programming formulation as follows:

Maximize:

$$\Sigma_r M_{ro} Y_{ro} \qquad (4)$$

Subject to constraint:

$$\Sigma_i N_{io} X_{io} = 1.0 \qquad (5)$$

$$\Sigma_r M_{ro} Y_{rj} - \Sigma_j N_{io} X_{ij} \quad => \quad 0 \text{ for all j} \qquad (6)$$

where M_{ro}, N_{ko} are a new transformed set of weights.

This completes the mathematical formulation of the unbounded DEA model.

Bounded DEA Model

As previously suggested, an additional restriction on the weights can be imposed. This restriction leads to the new bounded DEA class of models. If the upper and lower bounds tend to the same value, the bounded DEA model becomes a Common Set of Weights model used in evaluation of efficiencies in industrial processes.

Adding the following constraints to the linear programming formulation of the DEA (4 - 6) completes the development of the bounded model.

$$M_{ro} \quad - \quad T\,(MU)_r \Rightarrow 0 \text{ for all } r$$
$$M_{ro} \quad - \quad T\,(ML)_r \leq 0 \text{ for all } r$$
$$N_{ko} \quad - \quad T\,(NU)_k \Rightarrow 0 \text{ for all } k$$
$$N_{ko} \quad - \quad T\,(NL)_k \leq 0 \text{ for all } k$$

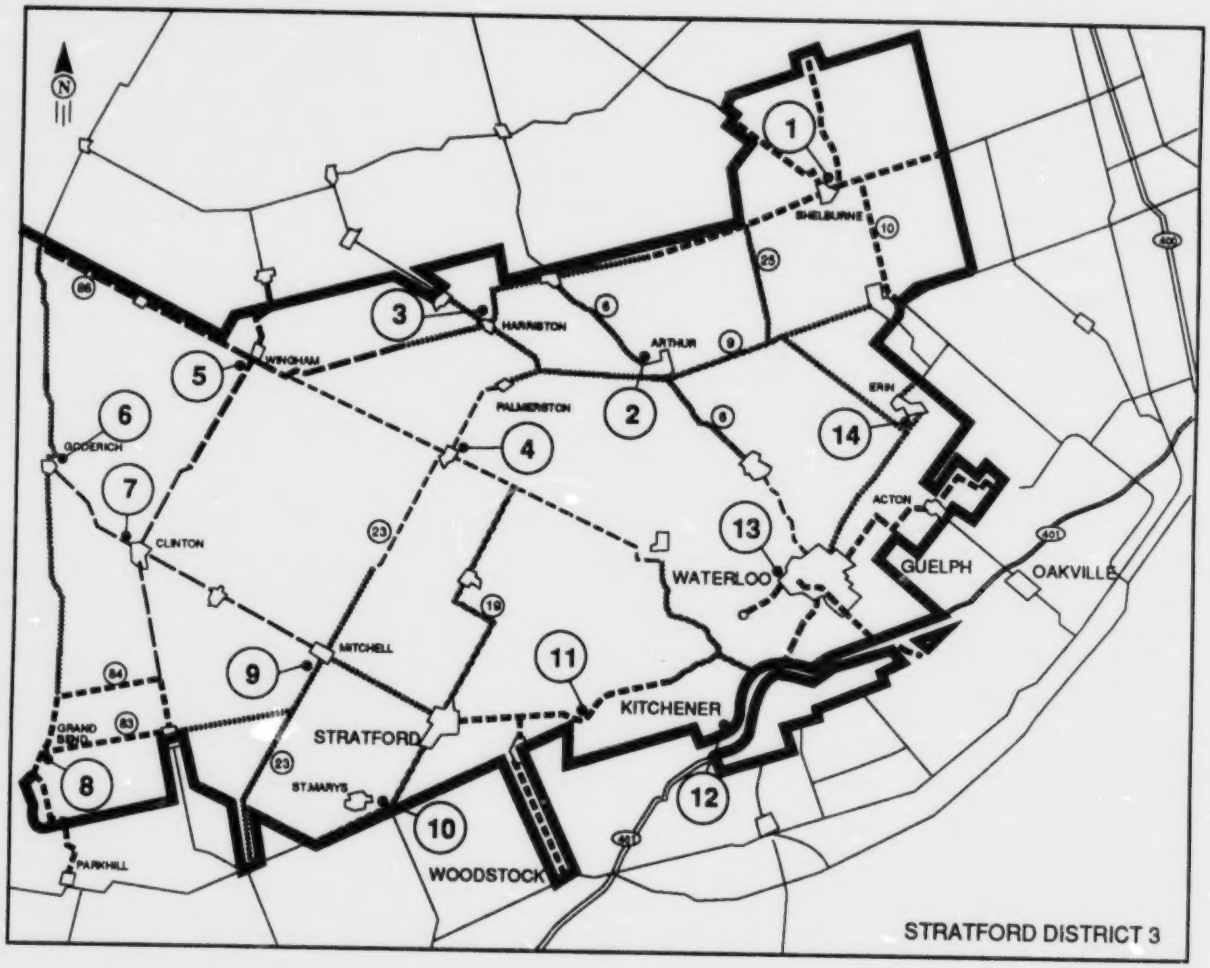
where $(MU)_r$, $(ML)_r$ and $(NU)_k$, $(NL)_k$ are upper and lower bounds imposed on the weights and T is the transformation factor.

A sample of the specific LP formulation for the set of 14 patrols is given on the next page. The LP problems were solved using the LINDO package.

Computer Output for Solution of the Described Linear Programming Problem

```
MAX
413M1+24M2
ST
                696N1+80N2=1
696M1+39M2- 751N1-67N2<0
616M1+26M2- 611N1-70N2<0
456M1+17M2- 538N1-70N2<0
616M1+31M2- 584N1-75N2<0
560M1+16M2- 665N1-70N2<0
446M1+16M2- 445N1-75N2<0
517M1+26M2- 554N1-76N2<0
492M1+18M2- 457N1-72N2<0
558M1+23M2- 582N1-74N2<0
407M1+18M2- 556N1-64N2<0
402M1+33M2- 590N1-78N2<0
350M1+88M2-1074N1-75N2<0
581M1+64M2-1072N1-74N2<0
413M1+24M2- 696N1-80N2<0
   1000M1                      - 2.1T<0
  -1000M1                      + 0.8T<0
         1000M2                -10.0T<0
        -1000M2                + 0.5T<0
                 1000N1        - 2.5T<0
                -1000N1        + 0.9T<0
                       1000N2- 6.0T<0
                      -1000N2+ 0.3T<0
END
LEAVE
```

Appendix A2



= (e.g.) Road section assigned to patrol 4

4 = Patrol No.

• = Location of patrol

6 = Hwy No.

Figure 5/ Patrol zone areas

Appendix A3

Assignment Size Factor, ASF

ASF = Sum over all road sections serviced by patrol, of:

Length x TLE[2] x Coefficient for Road Type +

Length x TLE x Coefficient for Winter Operations +

Length x Shoulder Width x Coefficient for Shoulder Type +

Length x Coefficient for Other Operations (R.O.W., median, etc.)

Components of the assignment size were weighted as follows:

Component	Type	Coefficient	
Surface	1	1.97	per 1000 km TLE
	2,3	1.72	"
	4	.92	"
	5	.59	"
	6,7	.31	"
Winter ops.		3.14	per 1000 km TLE
Shoulder	2	.18	per 100 sq.m. of shoulder
	4	.12	"
	6	.14	"
R.O.W., median etc.		2.30	per 1000 km of road

[2] TLE - Two-Lane Equivalents

The types are those used in the highway inventory data, and the coefficients were determined from the corresponding expenditures in the fiscal year 1986-87. Coefficients represent the relative proportions of the total maintenance expenditure on the various components. For example, approximately three times as much money was spent on surface type 4 work as on surface types 6 and 7 (.92 versus .31).

Average Traffic Serviced, ATS

ATS = Sum over all road sections, of:
Length x AADT x 10^{-4}

Total Expenditure of Patrol, TEX

TEX = Sum of All Expenditure Accounts Linked to Patrol

Average Pavement Rating, APR

APR = (sum over all road sections of Length x TLE X PCR) divided by
(sum of Length x TLE)

Appendix A4

Factors for DEA Analysis

PATROL NO. 3-14

ROAD NO	SECTION LHRS		LENG. (KM)	SURFACE TLE	SURFACE TYP	SHOULD. WID	SHOULD. TYP	PCR	AADT	PT	FACTORS ASF	FACTORS PRL	FACTORS ATL	FACTORS PTL
1	16190	1.8	2.1	1.0	5	3.0	2	91	7600	9.6	13.8	191	160	15
2	16190	3.9	10.9	1.0	5	3.0	2	91	4400	9.6	71.6	992	480	46
3	24960	4.5	4.8	1.0	5	2.4	2	69	5400	5.0	31.0	331	259	13
4	24970	0.0	4.3	1.0	5	2.4	2	69	5100	5.0	27.8	297	219	11
5	24970	4.3	7.1	1.0	5	2.4	2	69	4300	5.0	45.9	490	305	15
6	24980	0.0	6.9	1.0	5	2.4	2	69	4300	10.0	44.6	476	297	30
7	24983	0.0	2.9	1.0	5	2.4	2	69	4900	10.0	18.7	200	142	14
8	24990	2.6	2.6	1.0	5	2.4	2	70	3600	12.0	16.8	182	94	11
9	25480	0.0	6.1	1.0	5	2.5	2	91	2600	2.9	39.5	555	159	5
10	25480	6.1	1.3	1.0	5	2.0	6	95	3950	12.0	8.2	123	51	6
11	25480	7.4	0.3	1.0	6	2.4	2	95	3850	12.0	1.9	29	12	1
12	25480	7.7	4.5	1.0	5	2.5	2	95	2000	12.0	29.2	428	90	11
13	25483	0.0	2.9	1.0	5	2.5	2	95	2000	12.0	18.8	276	58	7
14	25483	2.9	7.1	1.0	5	1.8	2	75	1050	11.0	45.1	533	75	8

ASSIGNMENT SIZE FACTOR	Y1=	413
TRAFFIC SERVICED (V*KM)	Y2=	24
TOTAL MTCE EXPENDITURE	X1=	696
AVE. PAVEMENT RATING	X2=	80
AVE. % OF TRUCKS		8.1
AVE. % PRIVATIZATION		37.5

Appendix A5

Output for Solution of Linear Programming Problem for Patrol 14 of District 3

```
MAX      413 M1 + 24 M2
SUBJECT TO
   2)     696 N1 + 80 N2 =     1

     LP OPTIMUM FOUND  AT STEP      1

          OBJECTIVE FUNCTION VALUE

 1)         0.613666832

VARIABLE            VALUE          REDUCED COST
       M1          0.000861          0.000000
       M2          0.010759          0.000000
       N1          0.001077          0.000000
       N2          0.003126          0.000000
        T          1.075853          0.000000

ROW                 SLACK          DUAL PRICES
   2)               0.000000          0.613667
   3)               0.000000          0.195551
   4)               0.067252          0.000000
   5)               0.223135          0.000000
   6)               0.000000          0.479886
   7)               0.281218          0.000000
   8)               0.157930          0.000000
   9)               0.109803          0.000000
  10)               0.100372          0.000000
  11)               0.130707          0.000000
  12)               0.255186          0.000000
  13)               0.178512          0.000000
  14)               0.143652          0.000000
  15)               0.197758          0.000000
  16)               0.386333          0.000000
  17)               1.398609          0.000000
  18)               0.000000          0.018713
  19)               0.000000          0.001497
  20)              10.220608          0.000000
  21)               1.612191          0.000000
  22)               0.109174          0.000000
  23)               3.328871          0.000000
  24)               2.803494          0.000000

NO. ITERATIONS=      1
```

Note that the weights assigned to the two outputs are M_1=0.000861 and M_2=0.010759. Those corresponding to the inputs are N_1=0.001077 and N_2=0.003126.

It is worth pointing out that the "slacks"measure the extent to which the left-hand side of each constraint (p.2 of Appendix A1) falls short of the right-hand side. The "row" numbers refer to the particular constraint in question. Row 2, for example, refers to the first constraint (row 1 is the objective function). Of course, since constraint 1 is an "equality", then the slack is 0. It is noted that the slacks for rows 3 and 6, or constraints 2 and 5, are also equal to 0. These constraints pertain to the ratios associated with patrols 1 and 4. Since the slacks are zero, these ratios equal 1. Therefore, patrols 1 and 4 form the peer group for patrol 14. (See Table 4). The remaining slacks have no particular geometric significance for patrol 14.

The "reduced cost" and "dual prices" information is not relevant to our purposes in this problem.